NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4270

A PERFORMANCE ANALYSIS OF METHODS FOR HANDLING EXCESS INLET FLOW AT SUPERSONIC SPEEDS

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SUMMARY

A comparison was made of several methods for handling excess inlet flow for the Mach number range from 1.5 to 4.0. The following techniques were examined and evaluated in terms of their respective thrust penalties for an assumed turbojet engine: normal- and olique-shock spillage, bypassing through an auxiliary exit, bypassing to an ejector exhaust nozzle, and, finally, bypassing the excess flow through an auxiliary ramjet engine. Charts are presented for estimating these penalties at several Mach numbers.

For a hypothetical Mach 4.0 turbojet application, excessively high thrust penalties were incurred with spillage behind a normal shock or behind an oblique shock generated by a 30° half-angle cone. Use of a lower cone angle reduced the oblique-shock penalty, but at the expense of increased translation distances. Bypass drags remained relatively low over the entire Mach number range.

In some cases, heat addition to the bypass air can result in considerable thrust augmentation. For the Mach 4.0 turbojet considered herein, this dual-cycle system could yield gains of as much as 50 percent in net thrust at Mach numbers between 2.0 and 3.0.

INTRODUCTION

Operation of turbojet-powered aircraft over a wide range of supersonic speeds and ambient temperatures creates a problem of matching the inlet airflow to the particular schedule demanded by the engine (refs. 1 to 3). For most high Mach number applications, the inlet is generally sized for the high-speed condition and must have provisions for spilling or diverting excess air around the engine at "off-design" conditions. In addition, some inlets may require flow spillage even at "on-design" conditions to provide boundary-layer control in order to achieve high performance at high Mach numbers. For both cases, an efficient (i.e., low drag) technique must be employed for discharging the excess flow that is captured by the inlet and that is not actually required by the engine; otherwise, the over-all performance may be seriously reduced.

Various methods for handling such excess inlet flows have been proposed and will be examined in detail herein. Generally, they fall into either of two categories. The first consists of methods involving spillage behind the inlet shock system. In these cases, the excess air is deflected overboard around the inlet cowl by means of either oblique or bow shocks, or combinations thereof. The associated spillage, or additive, drags are defined by the pressure integral along the limiting streamline from the free stream to the cowl lip. The second category consists of the various bypass systems in which the excess air is taken aboard through the inlet and then ducted overboard through an auxiliary exit or bypassed around the engine to an ejector exhaust nozzle as its secondary stream. The drags of these systems are based on the total axial momentum change between the discharge station and the free stream. Other proposals have been advanced whereby the excess inlet flow is bypassed around the engine to the aft end of the powerplant installation. However, instead of serving as the secondary fluid in the ejector, the excess flow could be put to other uses; such as base bleed, divergent-nozzle injection to promote separation, etc. These latter proposals merit consideration, but are beyond the scope of this paper.

Instead of incurring thrust penalties due to spillage or simply bypassing, it would seem desirable to put any excess inlet flow through a ramjet cycle before discharging it overboard and, thereby, to achieve some degree of thrust augmentation. This scheme is, of course, similar to the bypass-engine or turbofan principle except that it is applied herein as a means of handling excess inlet flow. Undoubtedly, the mechanical and structural problems would be severe. However, where these particular problems are beyond the scope of the present cursory analysis, only the potential performance gains will be considered.

Some of the problems associated with each of these methods for handling excess inlet flows are discussed herein and their relative performance penalties are compared. The thrust penalties of each system have been computed for a representative turbojet engine. The trends, however, are believed fairly general even though the absolute levels may vary slightly with different engines.

SYMBOLS

The following symbols are used in the report:

A area, sq ft

A_0 free-stream tube area, sq ft

C_{F_n} engine net-thrust coefficient, $\frac{F_n}{q_0 A_0}$

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C_f	auxiliary-exit jet-thrust coefficient, $\frac{\text{Actual axial thrust}}{\text{Theoretical jet thrust}}$
D	drag, lb
d	diameter, ft
d_s/d_p	ratio of ejector secondary to primary nozzle diameters
F_n	engine net thrust, lb
$F_{n,p}$	thrust of primary stream (ideal nozzle expansion)
l	spike translation distance from shock-on-lip position, ft
M	Mach number
m	mass-flow rate
m_b/m_0	spillage or bypass mass-flow ratio
m_0	maximum possible mass-flow rate, $\rho_0 V_0 A_i$
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
q	dynamic pressure, $\frac{\gamma}{2} pM^2$, lb/sq ft
T	total temperature, $^{\circ}$R
t	static temperature, $^{\circ}$R
V	velocity, ft/sec
$\frac{w_s \sqrt{T_s}}{w_p \sqrt{T_p}}$	corrected ejector weight-flow ratio
γ	ratio of specific heats for air
θ	cone half-angle, deg
λ	auxiliary-exit discharge angle, deg
ρ	density, slugs/cu ft

Subscripts:

b	spillage or bypass flow
i	inlet cowl-lip station
p	primary

s secondary

0 free stream

3 compressor face

4 exit of constant-area bypass ramjet section

RESULTS AND DISCUSSION

The performance penalties of the various methods for handling excess inlet airflows will now be considered in detail. The associated drags are presented as a percentage of net engine thrust for a hypothetical turbojet engine, operating under the assumed conditions shown in table I. Flight occurs in the tropopause (altitudes above 35,000 ft) with an ambient temperature t_0 of 392° R. A constant nozzle-exit temperature of 3500° R is also assumed.

Shock Spillage

When an inlet is oversized and no other means of handling the excess inlet flow is provided, the engine will force the inlet to operate subcritically. The resulting bow-shock spillage is undesirable. Based on the techniques of reference 4 and as shown in figure 1, the additive drag associated with such spillage is excessive. In addition, the expulsion of the normal shock is often accompanied by inlet buzz, or shock instability.

If the excess flow were spilled behind an oblique shock, such as would occur by translating the centerbody forward ahead of the cowl, the additive drag would be considerably reduced (fig. 1). Whereas the cone half-angle has very little effect on the bow-shock additive drag, its effect on oblique-shock additive drag is significant. The reduction of the oblique-shock thrust penalty with cone angle is shown in figure 2. These curves were computed from the method of reference 4. It is evident in the figure that low-angle cones result in low thrust penalties. For example, at a free-stream Mach number of 1.5 and 70 percent spillage, the thrust penalty would be reduced from 49 percent (of engine net thrust) to 7 percent if the cone half-angle were reduced from 30° to 10°.

In order to obtain large amounts of oblique-shock spillage with the relatively low-angle cones shown in figure 2, a large amount of spike translation is required (fig. 3). At a free-stream Mach number of 1.5, in order to spill 70 percent of the mass flow, a 30° half-angle cone would have to be translated (from the shock-on-lip location) 0.45-inlet-diameter.

If the cone had a half-angle of 10°, it would have to be translated 1.80 diameters for the same spillage. Thus, although the drag would be considerably lower, a low-angle cone would require much greater translation. The choice of cone angle for a particular inlet configuration will generally be made on the basis of optimum inlet performance. The drags of high-performance external-compression inlets (i.e., the double-cone and the isentropic configurations) are generally bracketed by the oblique- ($\theta = 30^{\circ}$) and bow-shock values. Figures 2 and 3 do indicate that both the spillage thrust penalty and the amount of spike movement must be considered by the designer if inlet-engine matching is to be achieved by a movable compression surface.

Bypass Through an Auxiliary Exit

Instead of spilling the excess inlet flow ahead of the inlet, the bypass system allows the inlet to capture the maximum airflow corresponding to its most efficient, or critical, operating point. If the auxiliary exit discharges the flow at some angle to the stream, it may or may not require an external flap. The associated drag could be avoided by eliminating the flap; however, the bypass system would still suffer from the effect of discharge angles (figs. 4 and 5).

In figure 4, data from several sources show experimentally determined thrust coefficients for auxiliary exits discharging at an angle to the free stream. It can be seen that axial thrust decreased more rapidly than the cosine of the discharge angle. Therefore, on the basis of these data it might be expected that an auxiliary exit discharging flow at a 15° angle would have only approximately 90 percent of the theoretical axial sonic thrust. A 25° flow discharge angle would similarly result in approximately 80 percent of the theoretical value for axial sonic thrust.

The effect of auxiliary-exit thrust coefficient on bypass thrust penalty is shown in figure 5. A 15° exit ($C_f = 0.9$) would result in a thrust penalty of about twice the ideal ($C_f = 1.0$) value at a free-stream Mach number of 2.0. If the auxiliary-nozzle thrust coefficient were only 0.8, the drag penalty would be even greater (fig. 5). At a Mach number of 4.0, the thrust penalties are much greater than at the lower Mach number even for the ideal sonic exit. The increase in thrust penalty results from the use of a greatly underexpanded sonic, or convergent, auxiliary nozzle, since the pressure ratio across the nozzle increased about tenfold as the Mach number increased from 2.0 to 4.0.

If the auxiliary nozzle were of the convergent-divergent type, the thrust penalty would, theoretically, be considerably reduced at the high Mach number (fig. 6). In an actual installation, such an exit may be mechanically impractical since the throat as well as the exit area of the nozzle must vary to change the bypass flow.

The preceding data were computed assuming bypass total pressures equal to the engine-face values (table I). However, it would be expected that in an actual installation the bypass pressure would be somewhat less. As shown in figure 7, the bypass thrust penalty is relatively insensitive to total-pressure losses especially at the high Mach number ($M_0 = 4.0$).

One of the most difficult problems associated with a bypass system is the duct size requirements if large quantities of air are to be handled. This is illustrated in figure 8, wherein the duct size for choking ($M = 1.0$) is shown for no total-pressure losses between the bypass duct and engine face. The duct size would increase with a reduction in tolerable duct Mach number and directly with total-pressure loss. As an example, if the bypass were required to handle 70 percent of the inlet flow at a Mach number of 1.5 the bypass duct would have to be at least 65 percent of the inlet cowl area. For this example, a 4-foot-diameter cylindrical-cowl inlet would have to allow almost a 1-foot annulus all the way around the engine to handle the bypass flow. 4617

Bypass to Ejector

Ejector pumping and thrust characteristics are generally considered in terms of corrected ejector weight-flow ratio $\left(\frac{w_s\sqrt{T_s}}{w_p\sqrt{T_p}}\right)$. The conversion between this parameter and the inlet bypass mass-flow ratio is shown in figure 9. Since the optimum (best thrust) weight-flow ratio is generally around 0.05 to 0.10, it can be seen that the use of high bypass flows results in the ejector handling more than the optimum secondary flow. This is best shown by figure 10, in which data presented in references 5 and 6 have been converted to a net-thrust parameter. The optimum bypass flow for the 1.4-diameter-ratio ejector would be about 0.10 at a Mach number of 2.0. Consequently, if more than this quantity is supplied to the ejector, its performance will be penalized. Higher-diameter-ratio ejectors may be more efficient at very high flows.

In order for the ejector to handle the desired flow, the secondary pressure must be compatible with the ejector pumping characteristics. For the ejectors previously considered, the total-pressure reductions shown in figure 11 would have to be provided. Although there should be sufficient total pressure available at a Mach number of 2.0 for both ejectors, it can be seen that a 1.2-diameter-ratio ejector could not be used to handle large amounts of bypass flow $\left(\frac{m_b}{m_0} > 0.38\right)$ at a Mach number of 1.5. Thus, the designer must consider the pumping ability of the ejector and the pressure available from the source. Some form of throttle would probably be required over part of the range. In some cases, a change in ejector geometry from that associated with peak thrust would be required to handle the bypass flow. This required geometry change is especially evident for ejectors having divergent shrouds. Since the ejector performance would be reduced, a thrust penalty caused by handling the bypass flow would result.

Comparison of Performance Penalties

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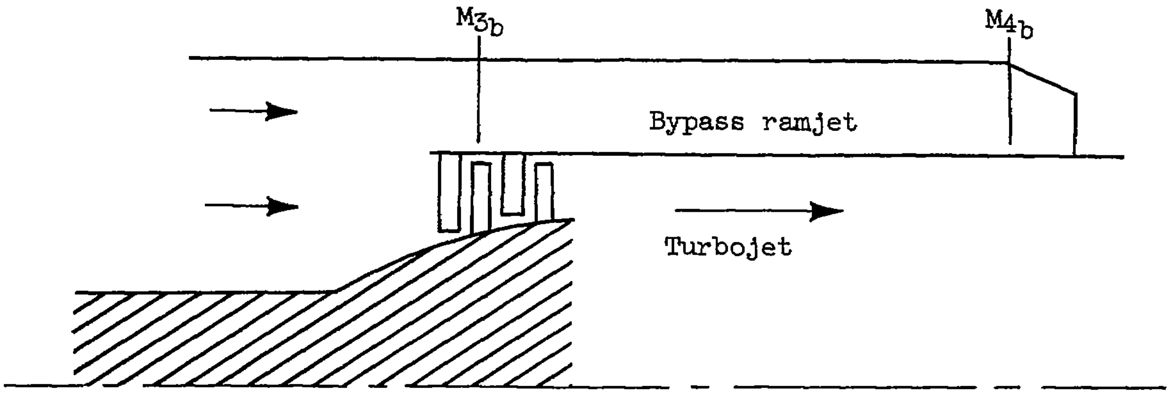
A comparison of the penalties associated with these various methods is presented in figure 12. The penalty associated with bow-shock spillage is obviously much higher than any other method. The effect of cone half-angle on net thrust penalties due to additive drag is shown by the curves for 15° and 30° cones. Whereas the 15° cone resulted in close to the minimum loss, the 30° cone had a loss that was second only to bow-shock spillage. The thrust losses associated with a reasonably efficient sonic bypass were relatively low except at the high Mach number ($M = 4.0$) where flow reexpansion in a convergent-divergent nozzle could be used in order to reduce the loss.

Another form of summary curve is presented in figure 13. Handling of the excess flow associated with a hypothetical ($M = 4.0$) turbojet engine and with a fixed cowl area has been analyzed for the various techniques described herein. The penalties associated with normal-shock and high cone-angle oblique-shock spillage are excessive. Bypassing to ejectors would result in relatively low penalties for the range where data are available. However, it appears that the thrust loss would be quite large at the low Mach numbers where the ejector would be called upon to handle high flows. Both the bypass and oblique-shock spillage with low-angle cones resulted in relatively low thrust losses over the engine range.

If a particular inlet geometry permits oblique-shock spillage with a low-angle cone, it appears that minimum thrust losses will occur. Otherwise, the use of the bypass system would appear desirable so long as there is sufficient space for the necessary ducting and care is exercised in the auxiliary-exit design.

Bypass Ramjet

In order to illustrate the magnitude of potential thrust gains to be had with the addition of heat to the bypass air, a simplified analytical model was considered. This model is schematically shown in the following sketch:



$$A_{3_b} = A_{4_b}$$

It was assumed that the inlet cowl was cylindrical and that the capture area was equal to the total area at the compressor-face station, that is,

$$A_{3_b} + \overbrace{A_{3_{flow}} + A_{3_{hub}}}^{\text{Engine}} = A_i$$

Based on engine-inlet matching requirements, the inlet capture area A_i is generally greater than the engine tip area for Mach numbers above 2.0. The somewhat arbitrary assumption of a cylindrical cowl allows for a zero-lip-drag inlet and avoids the problem of additional external-fairing drags with either larger or smaller bypass ducts than those considered herein. It was further assumed that the maximum temperature in the bypass duct would be 3500° R. Thus, for each flight Mach number (ambient temperature of 392° R assumed) there would be a maximum temperature rise allowable. Otherwise, the heat addition would be defined by heating and choking in a constant-area passage.

The calculated performance for this arrangement is shown in figure 14. The solid lines represent the gain in net thrust if heat were added to the bypass flow consistent with the limits and assumptions already discussed. The dashed lines, on the other hand, represent the loss in thrust of the same bypass flow if no heat were added. Thus, the overall gain by adding heat to the bypass flow would be the difference between the two families of curves.

Presented in figure 15 is the over-all net-thrust increase, if heat is added to the bypass flow, required to match the hypothetical engine considered in figure 13. It can be seen that over-all gains of 50 percent in thrust would be possible at Mach numbers between 2.0 and 3.0. This gain, of course, necessitates a correspondingly large increase in the total fuel-flow rate. However, since the Mach 4.0 turbojet is likely to be a low-pressure-ratio engine, its specific fuel consumption (lb of thrust/lb of fuel/sec) at Mach 2.0 and 3.0 is not going to be much different from that of a conventional ramjet engine or of the bypass ramjet engine contemplated herein. Hence, the over-all specific fuel consumption of the dual-cycle system should not be significantly different from that of the single turbojet engine. Although the structural problems may be severe, it appears that the large potential thrust gains would merit further study.

SUMMARY OF RESULTS

The following results were obtained from an analysis of various means of handling excess inlet flow in the 1.5 to 4.0 flight Mach-number range.

1. For a hypothetical Mach 4.0 turbojet engine-inlet combination, excessively high thrust penalties were incurred with spillage behind a bow shock or behind an oblique shock generated by a 30° half-angle cone. Use of a lower-angle cone reduced the oblique-shock thrust penalty, but at the expense of increased translation distances for the centerbody. Bypass drags remained relatively low over the entire Mach number range.

2. At flight Mach numbers in excess of 2.0, the thrust penalty of bypass systems could be reduced considerably if the bypass flow were expanded in a convergent-divergent nozzle rather than just a convergent nozzle (sonic discharge).

3. Total-pressure losses in a sonic bypass duct did not markedly increase the thrust penalty but did increase the area requirements considerably.

4. Use of excess inlet flow in an ejector, rather than discharging the excess through an auxiliary exit, could result in low thrust loss.

5. Adding heat to the excess inlet flow before it is discharged through an auxiliary exit resulted in considerable propulsive-thrust increases. For a hypothetical Mach 4.0 turbojet, the dual-cycle system could yield gains of as much as 50 percent in net thrust at Mach numbers between 2.0 and 3.0.

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Cleveland, Ohio, February 24, 1958

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2. Schueller, Carl F.: Inlet-Engine Matching and Control Systems for Supersonic Airplanes. Paper presented at Journées Int. de Sci. Aéro. (Paris), May 27-29, 1957, pp. 27-28; discussion, pp. 29-41.

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6. Greathouse, W. K., and Hollister, D. P.: Preliminary Air-Flow and Thrust Calibrations of Several Conical Cooling-Air Ejectors with a Primary to Secondary Temperature Ratio of 1.0. II - Diameter Ratios of 1.06 to 1.40. NACA RM E52F26, 1952.

7. Dewey, Paul E., and Vick, Allen R.: An Investigation of the Discharge and Drag Characteristics of Auxiliary-Air Outlets Discharging into a Transonic Stream. NACA TN 3466, 1955.

TABLE I. - ASSUMED INLET AND ENGINE PERFORMANCE

[Nozzle exit temperature, 3500° R; ambient temperature, 392° R.]

Flight Mach number, M_0	Inlet pressure recovery, P_3/P_0	Nozzle pressure ratio, P/p_0	Engine net thrust coefficient, $C_{F_n} = \frac{F_n}{q_0 A_0}$
1.5	0.93	6.5	3.90
2.0	.90	10.0	2.81
3.0	.69	24.0	1.70
4.0	.50	70.0	1.03

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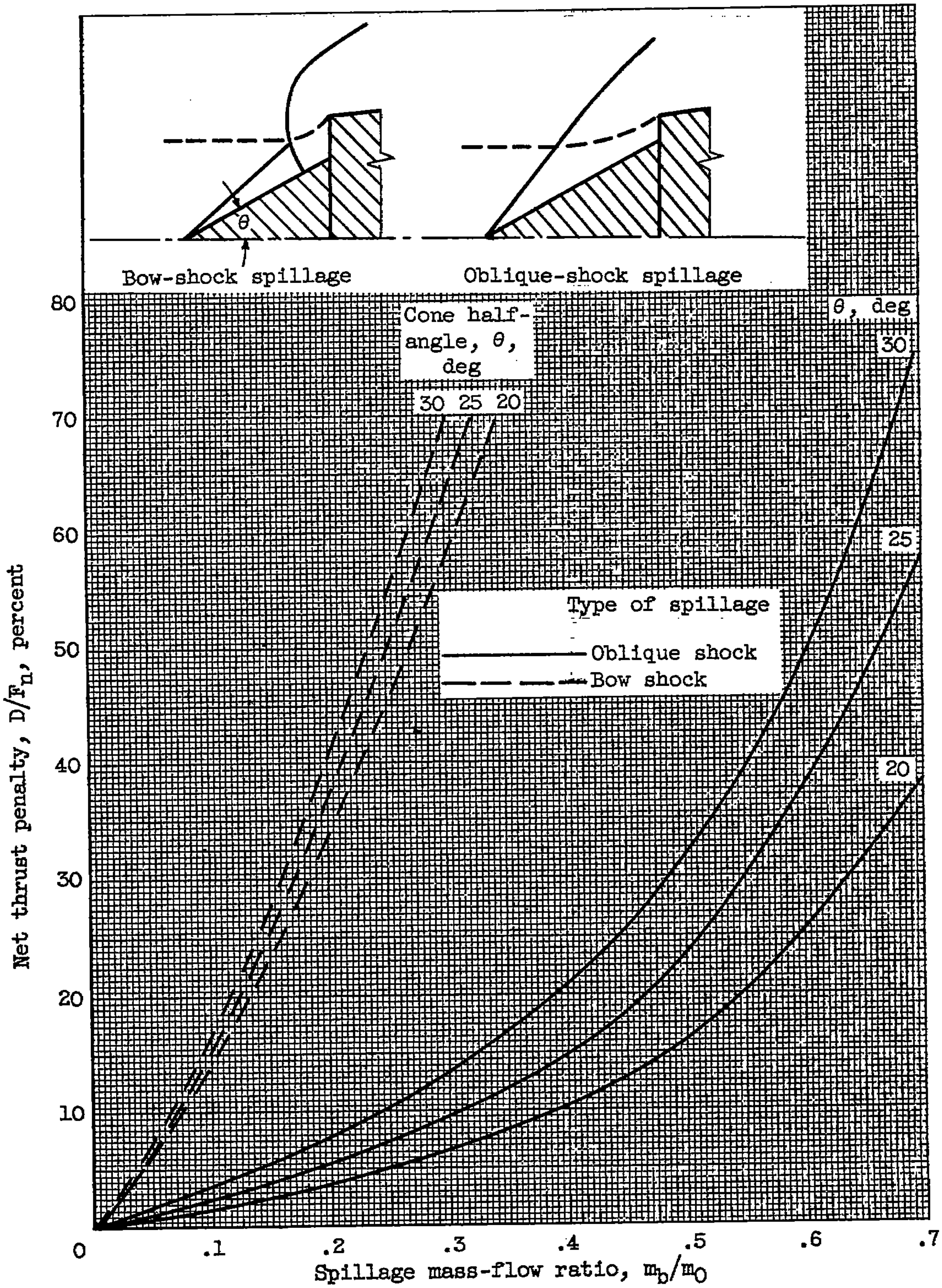

Figure 1. - Comparison of bow- and oblique-shock spillage penalties. Free-stream Mach number, 3.0.

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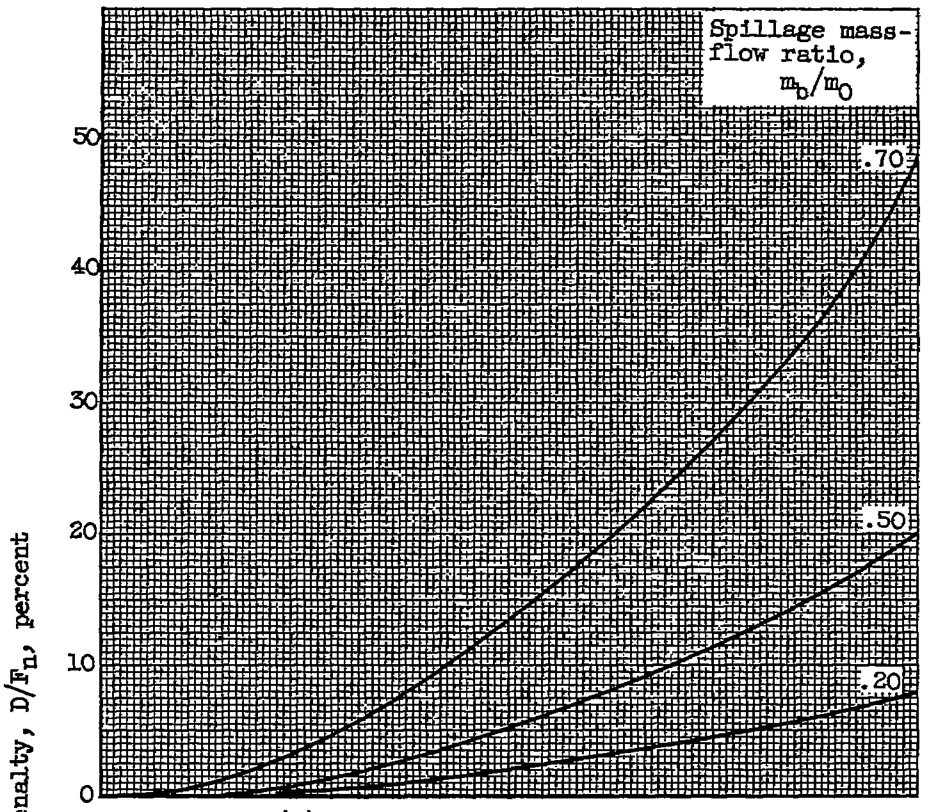
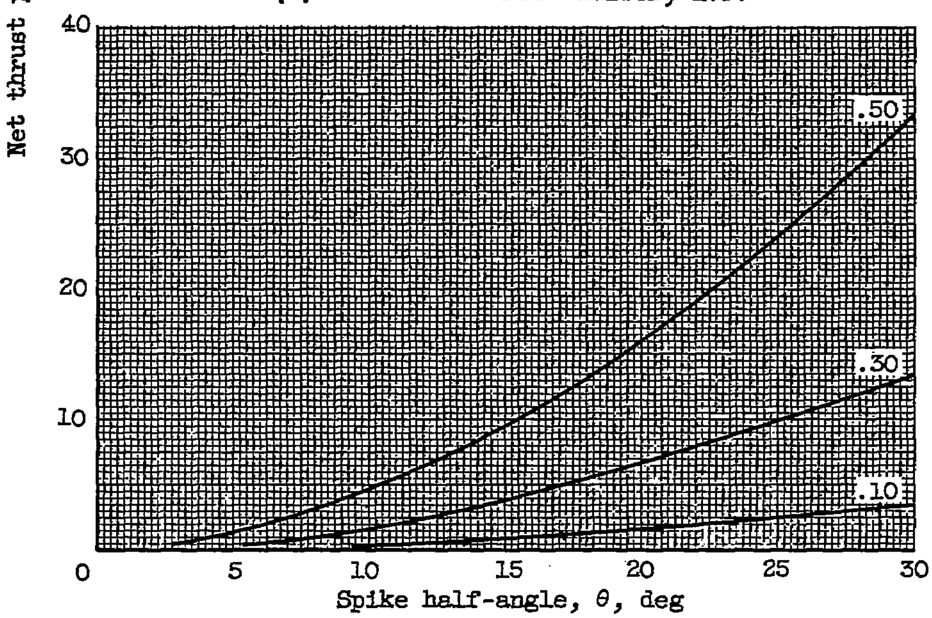
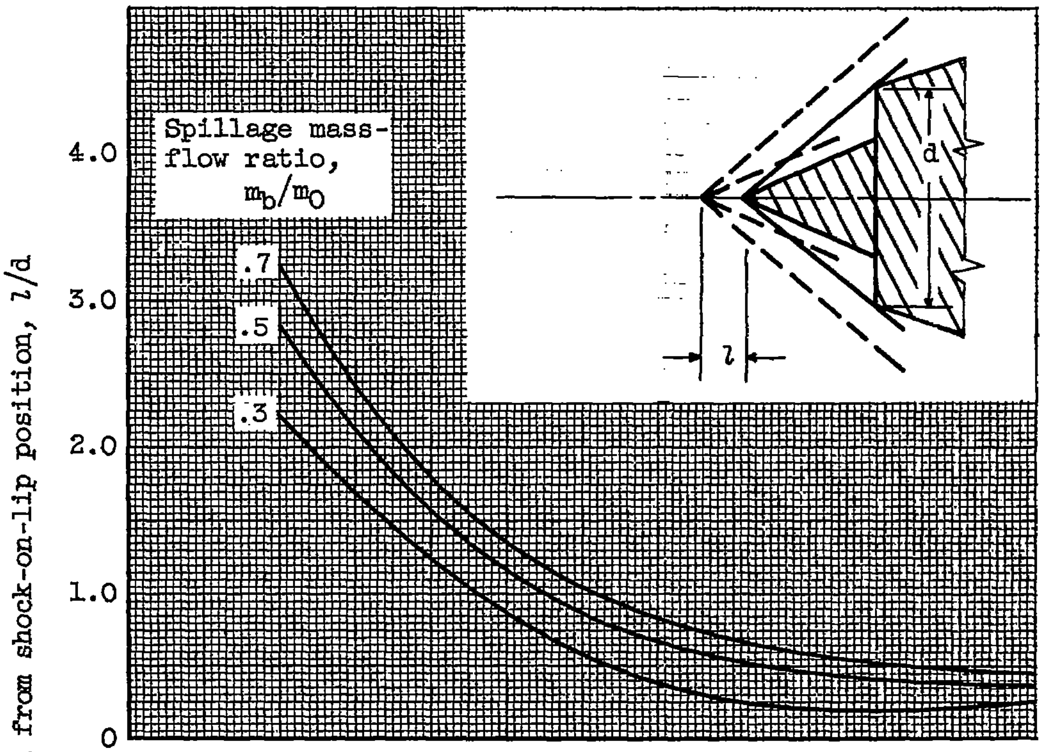


(a) Free-stream Mach number, 1.5.

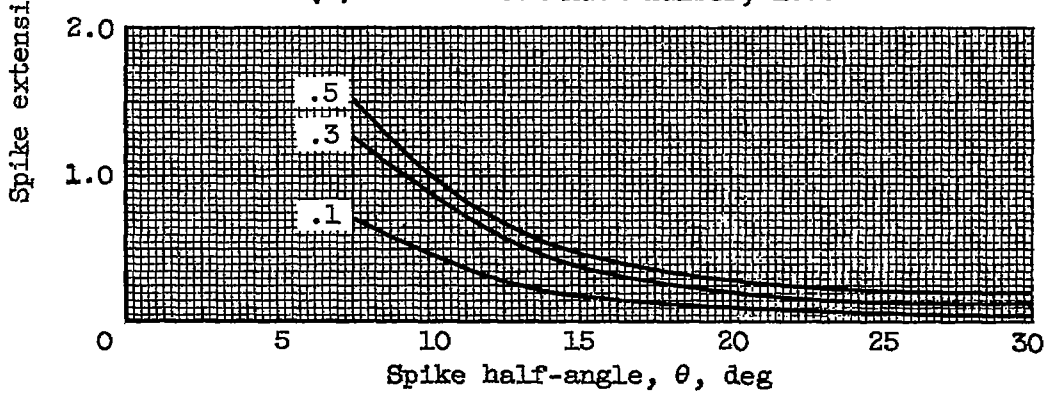


(b) Free-stream Mach number, 3.0.

Figure 2. - Effect of cone half-angle on oblique-shock spillage penalty.



(a) Free-stream Mach number, 1.5.



(b) Free-stream Mach number, 3.0.

Figure 3. - Spike extension required for oblique-shock spillage. Axisymmetric inlet.

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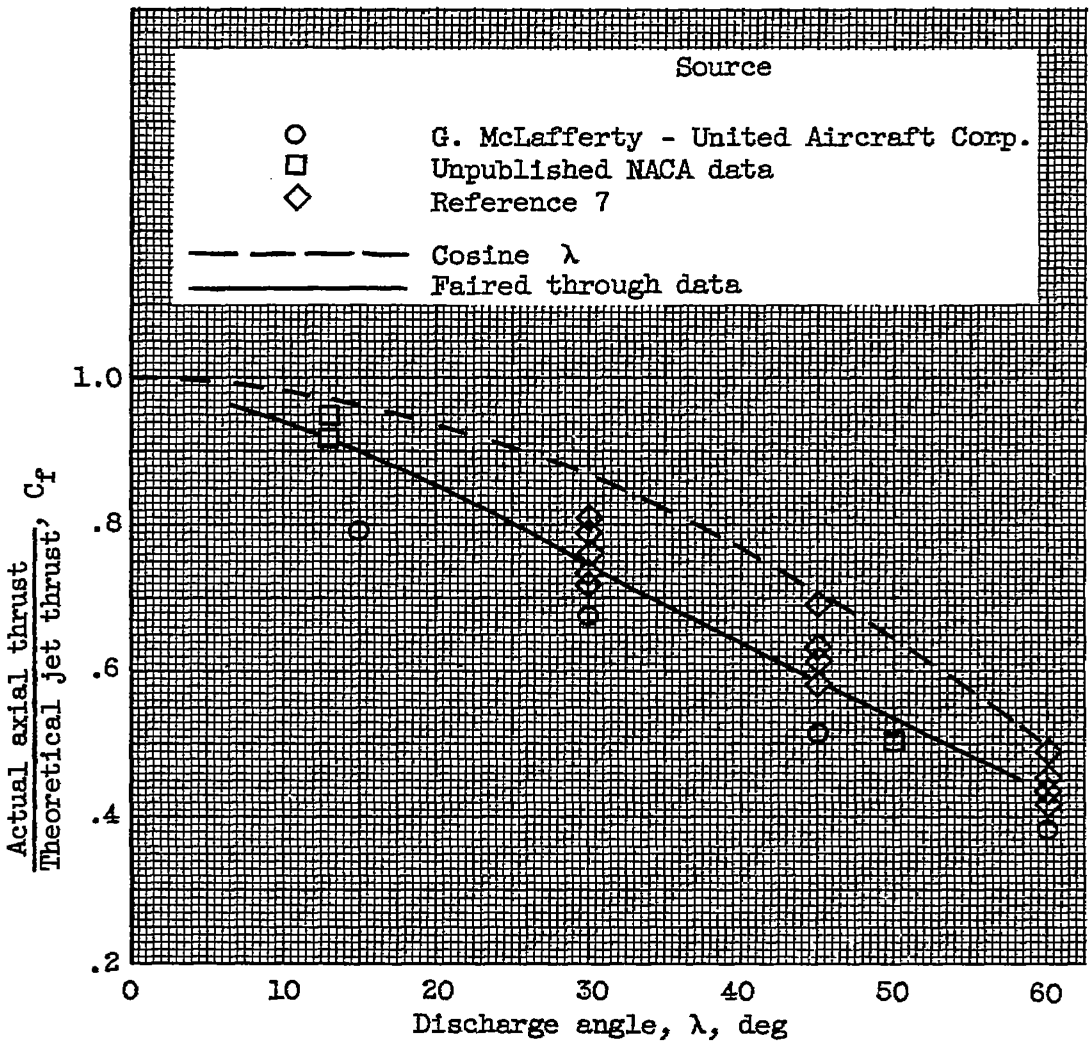

Figure 4. - Performance of auxiliary exits with sonic discharge conditions.

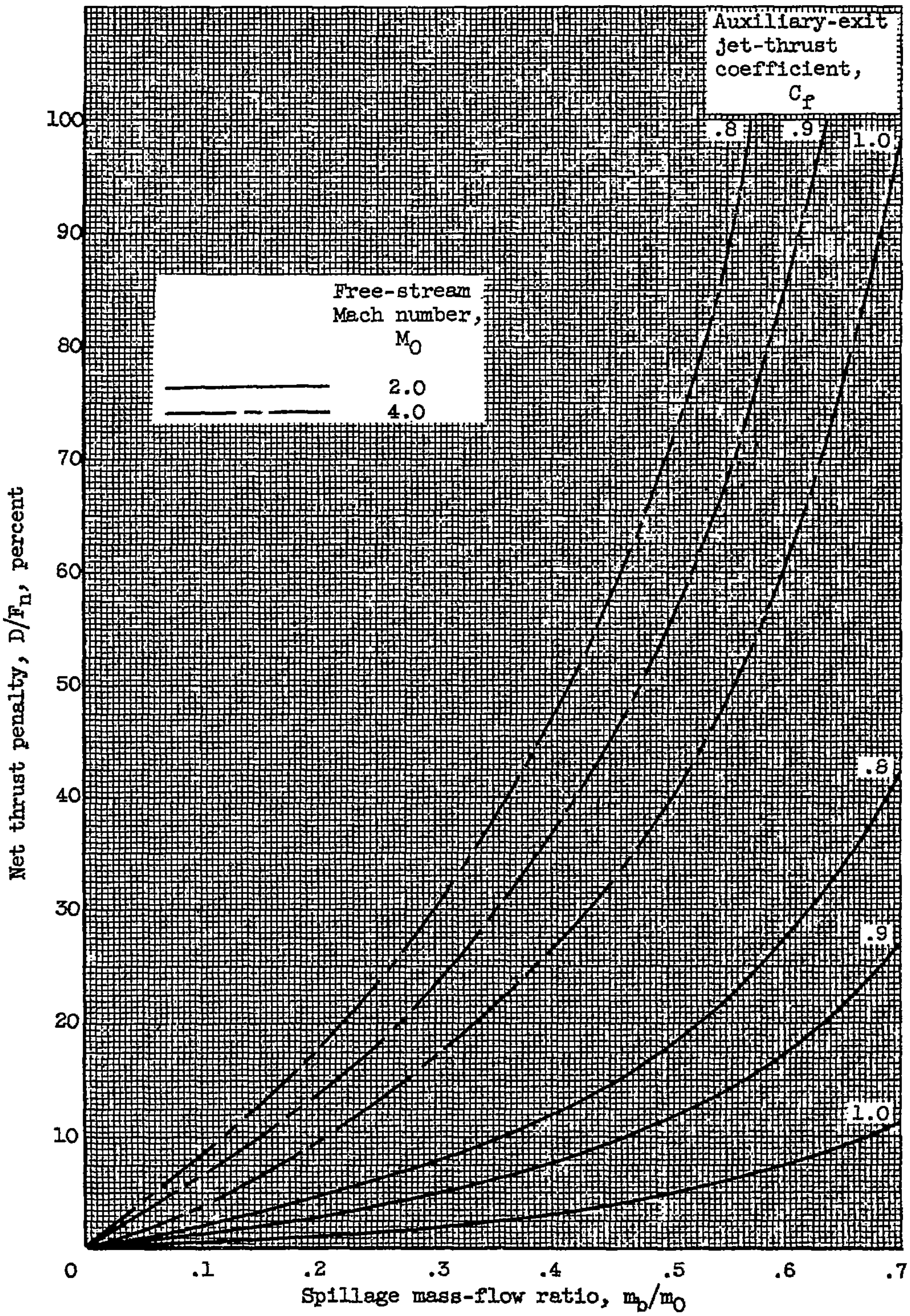

Figure 5. - Effect of auxiliary-exit performance on sonic-bypass thrust penalty.

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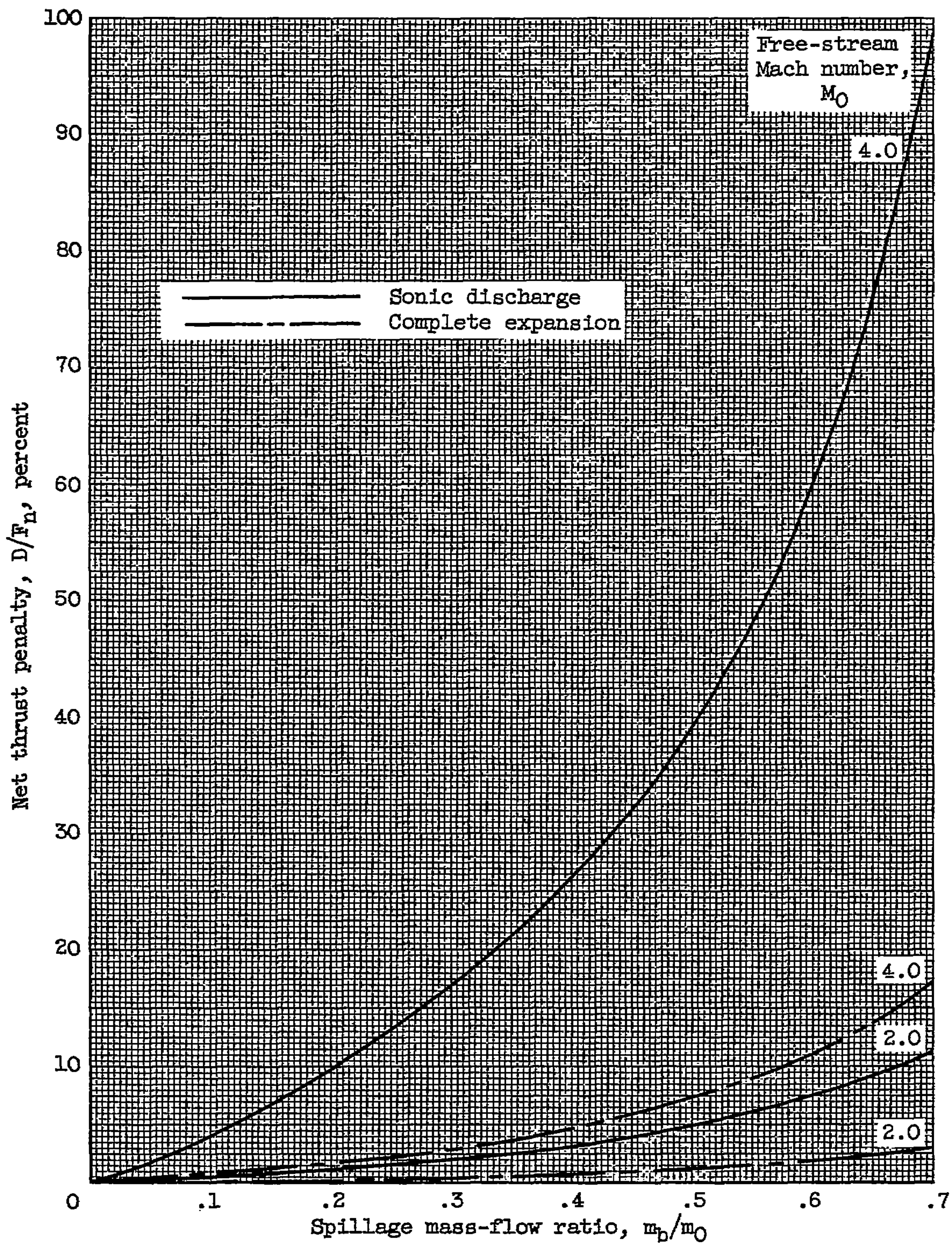
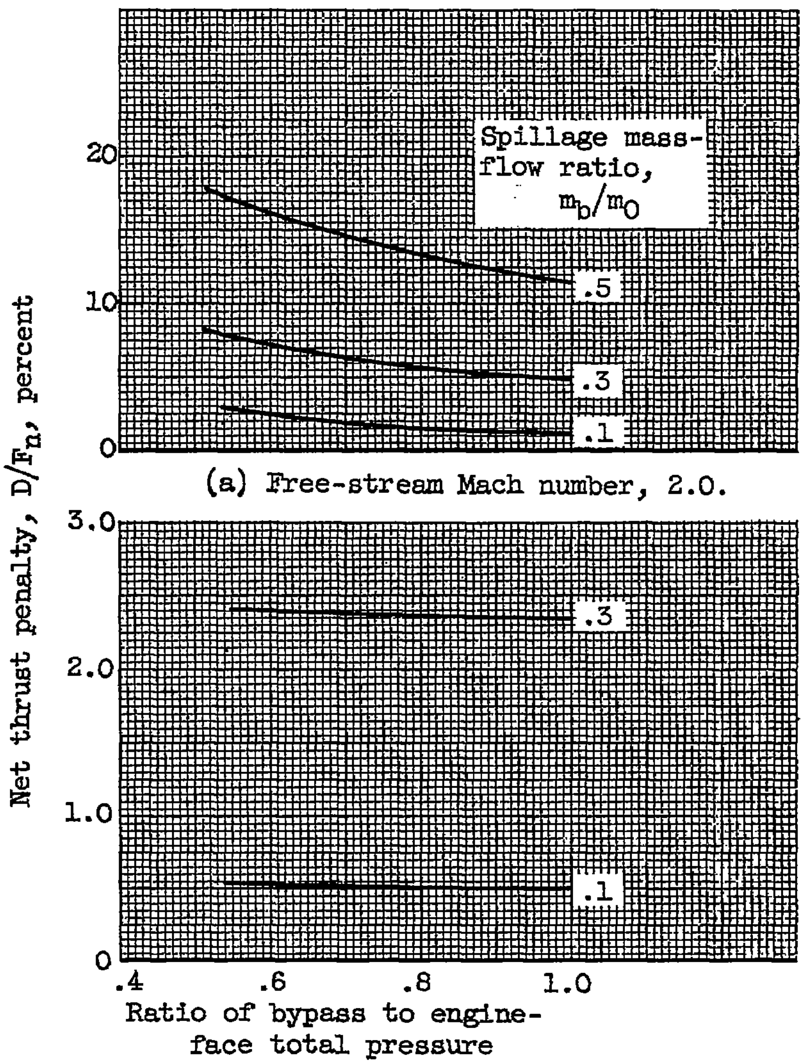


Figure 6. - Effect of auxiliary-exit reexpansion on bypass thrust penalty. Auxiliary-exit jet-thrust coefficient, C_f, 1.0.



(a) Free-stream Mach number, 2.0.

(b) Free-stream Mach number, 4.0.

Figure 7. - Effect of bypass pressure recovery on thrust penalty. Sonic bypass. Auxiliary-exit jet-thrust coefficient, C_f, 0.9.

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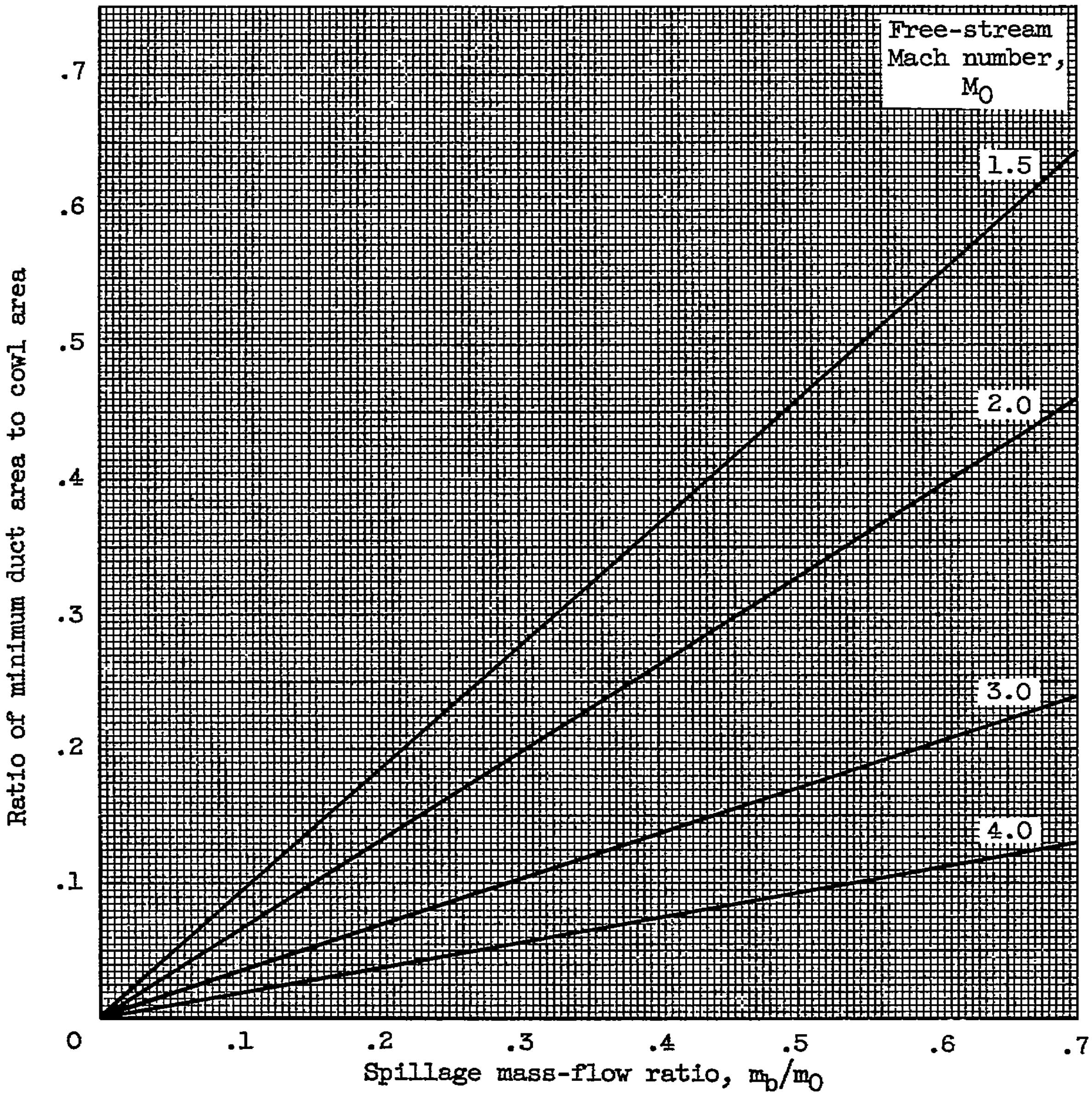

Figure 8. - Minimum bypass duct size. Ratio of bypass total pressure to engine-face total pressure, 1.0.

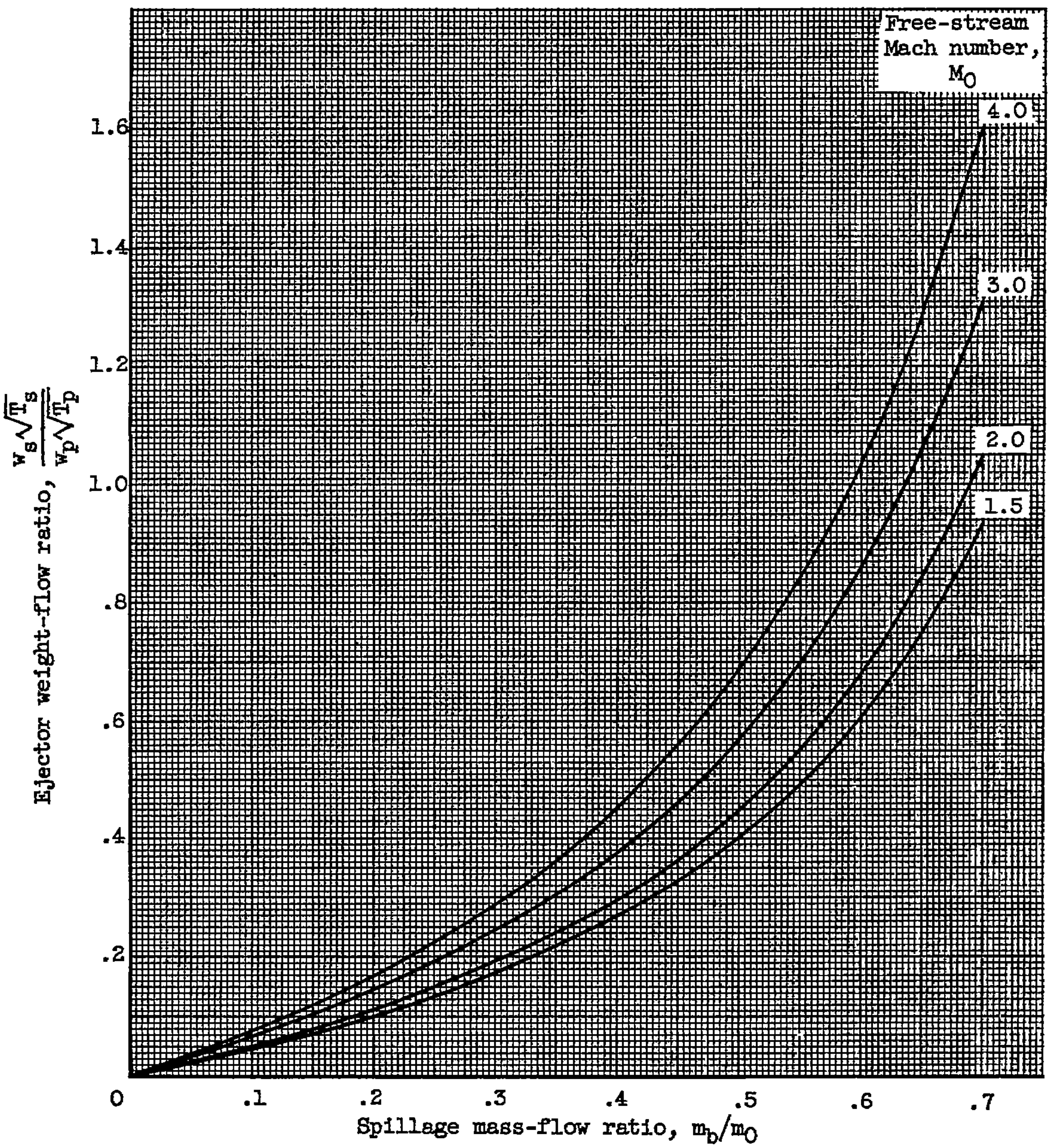

Figure 9. - Required ejector weight-flow ratio. Nozzle exit temperature, 3500° R; ambient temperature, 392° R.

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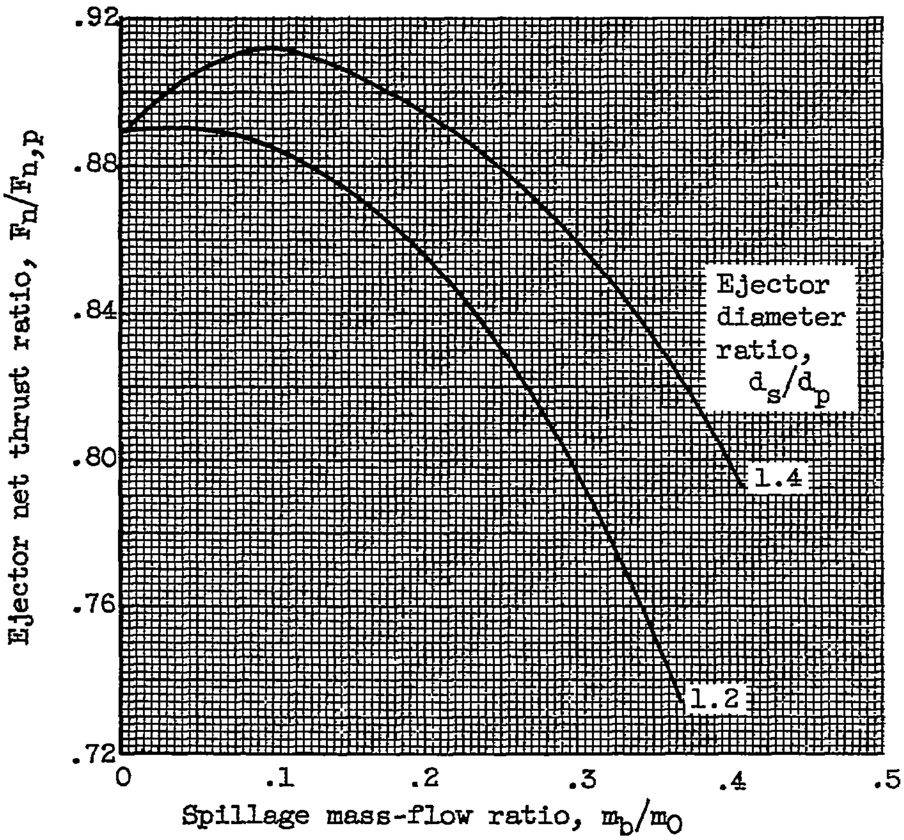
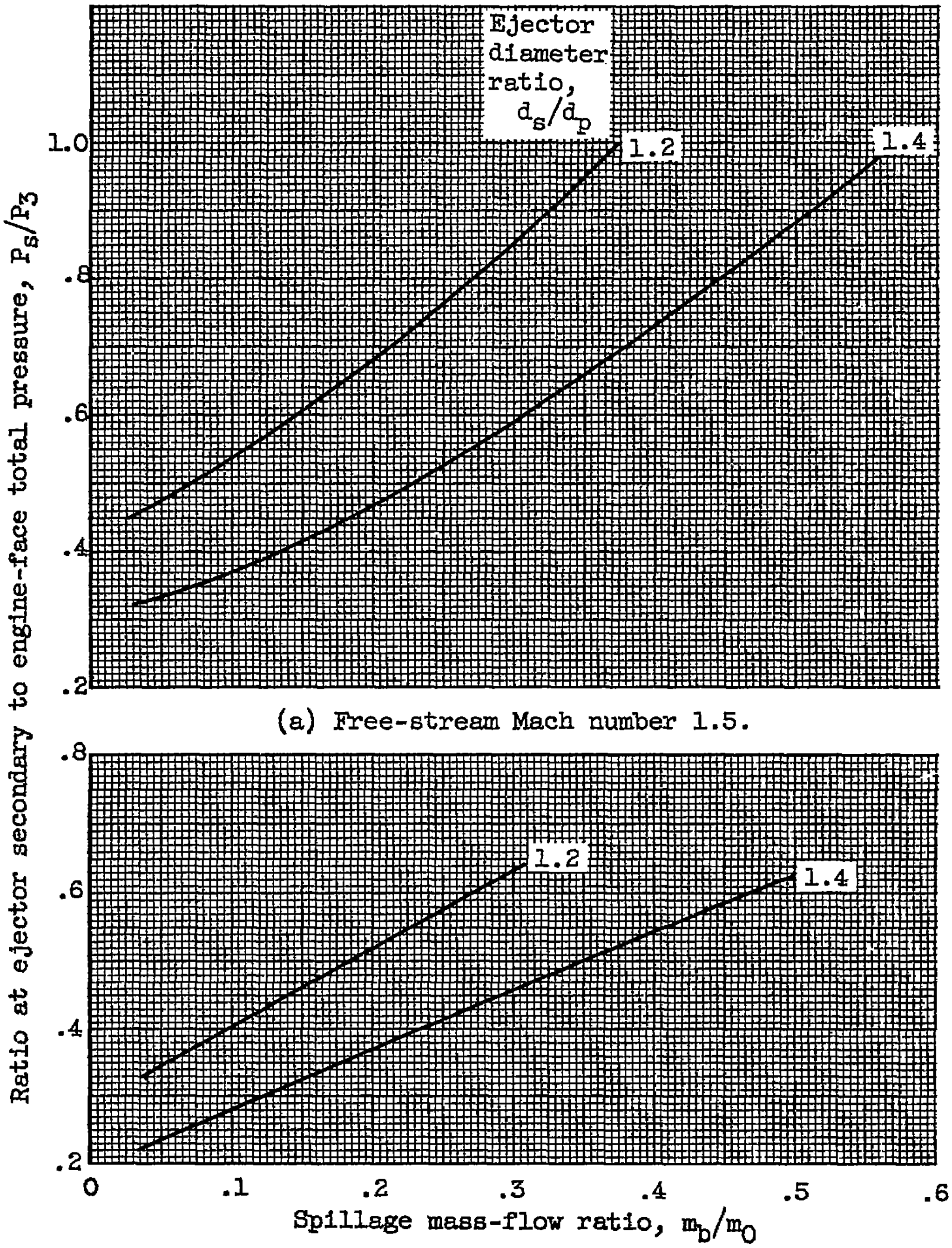


Figure 10. - Effect of secondary flow on ejector performance. Free-stream Mach number, 2.0.



(b) Free-stream Mach number, 2.0.

Figure 11. - Total-pressure loss to match bypass flow with ejector.

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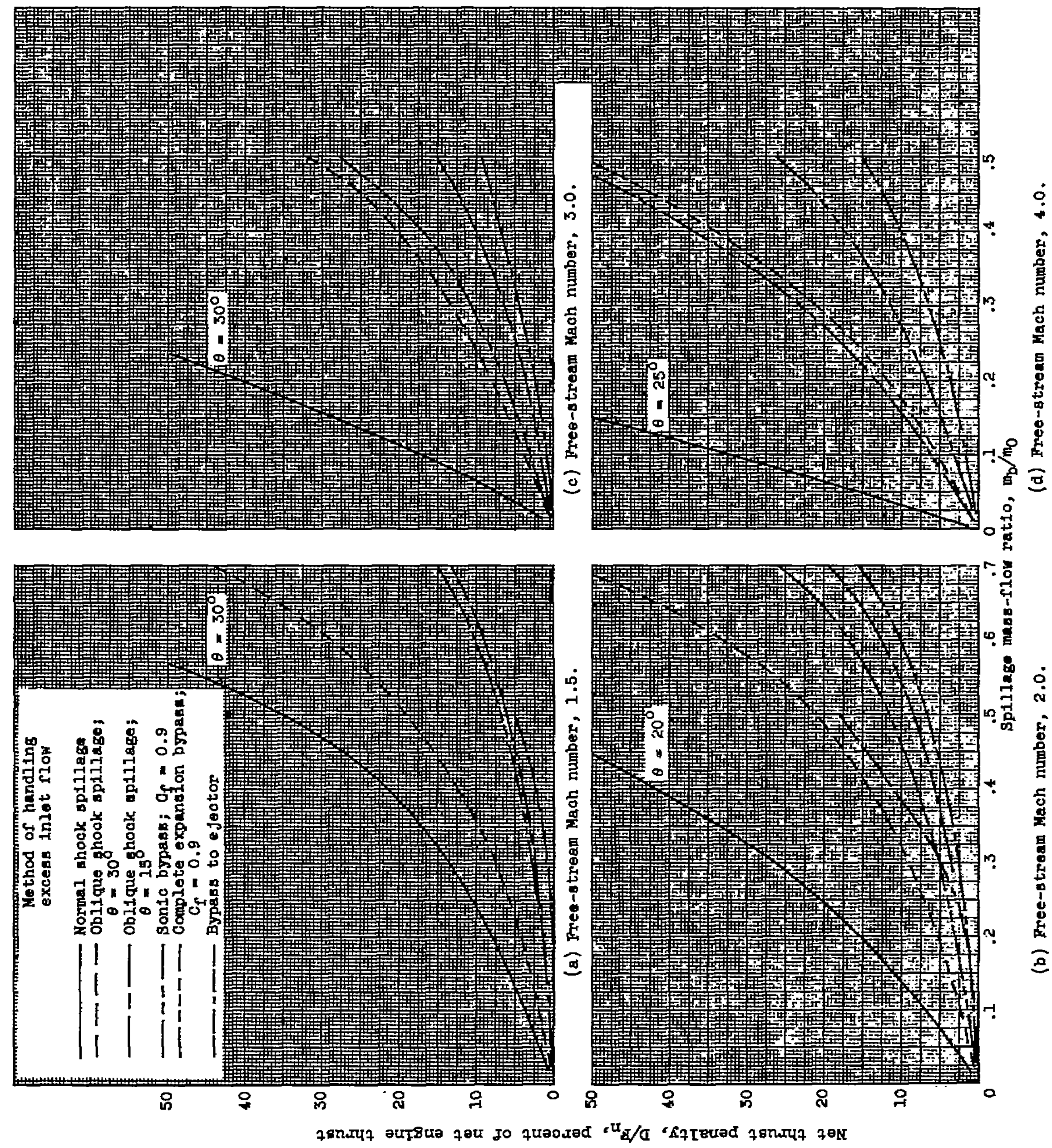

Figure 12. - Comparison of thrust penalties for various spillage methods.

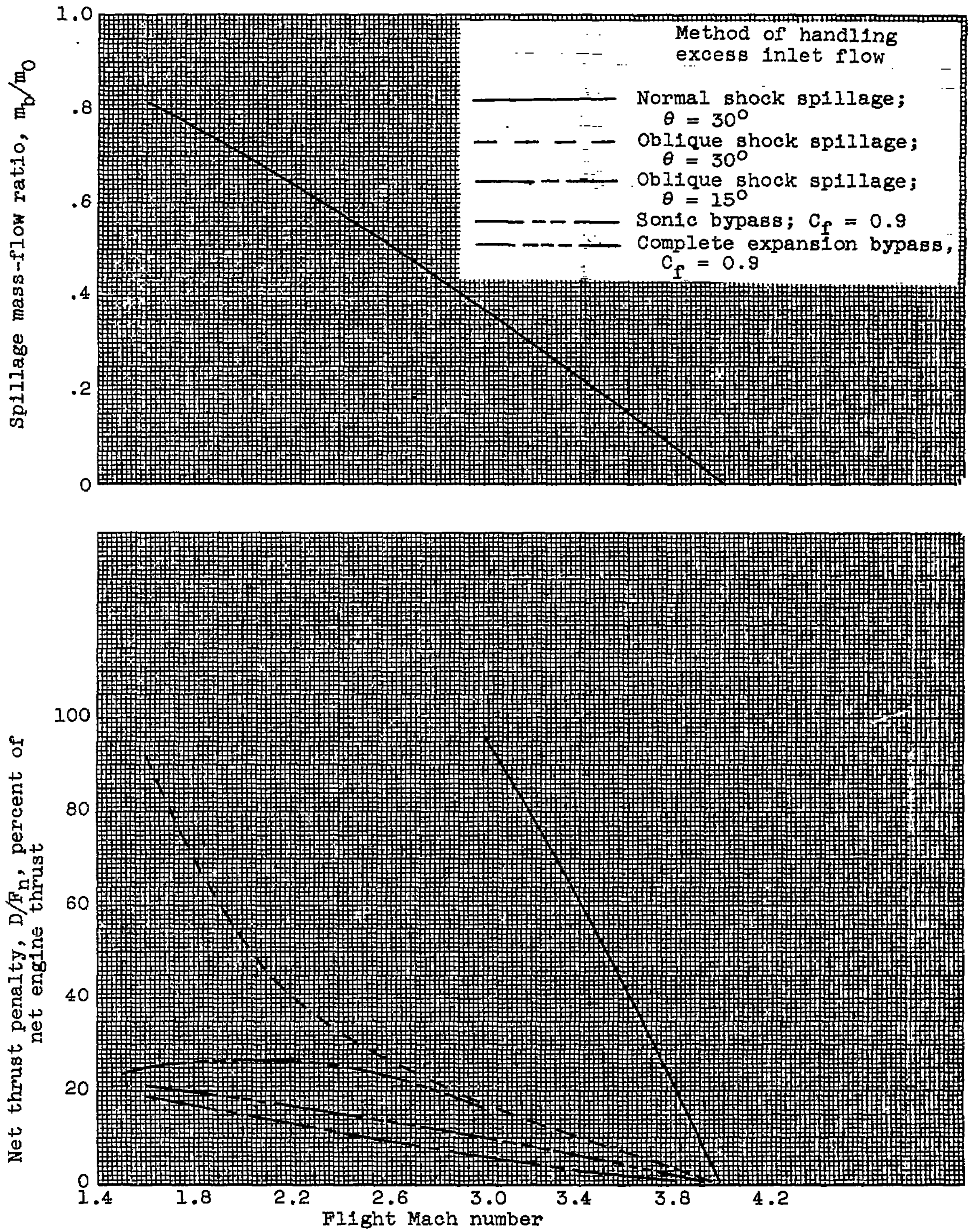

Figure 13. - Comparison of spillage penalties for hypothetical free-stream Mach 4 inlet-engine combination.

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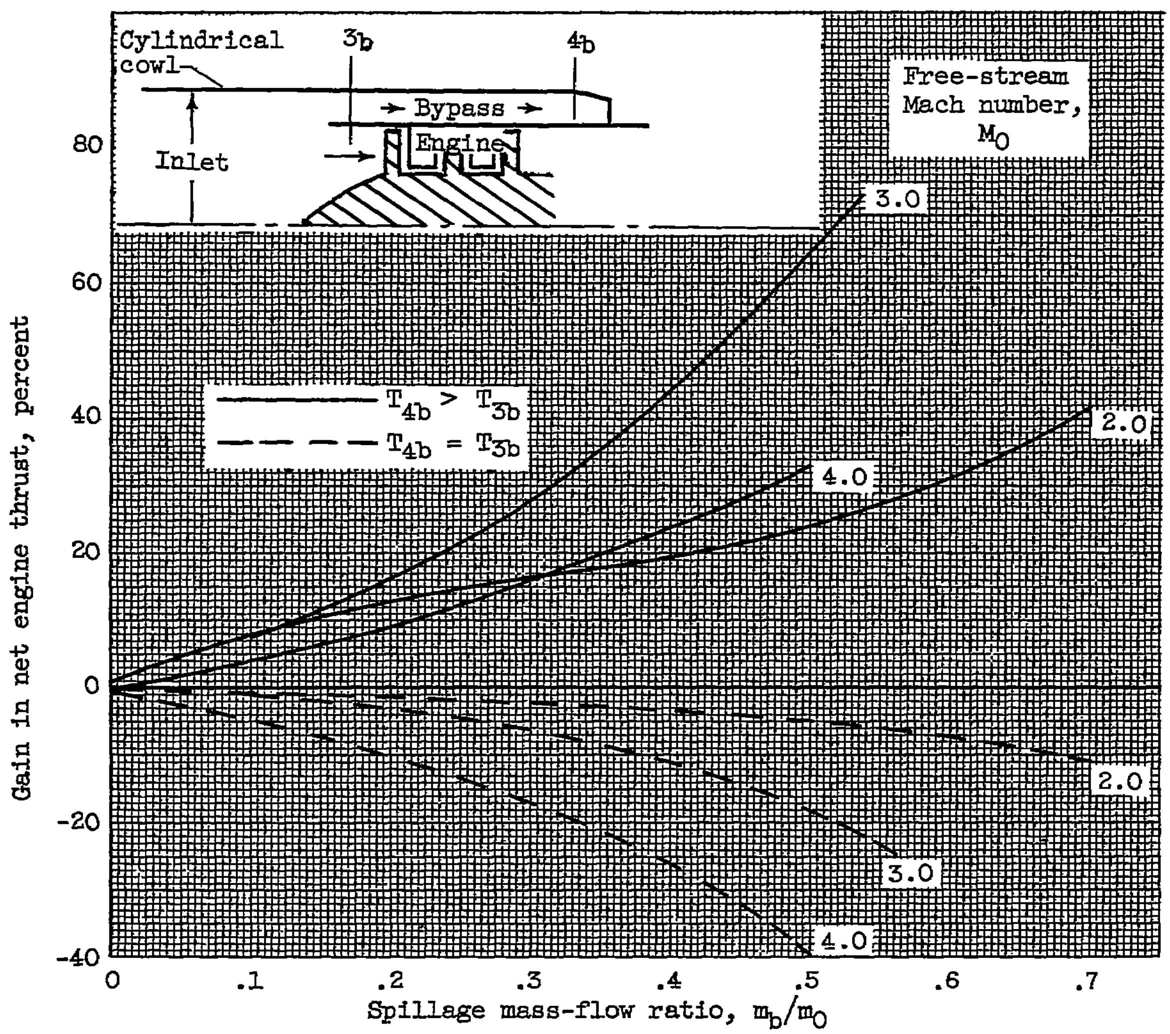

Figure 14. - Gain in thrust by adding heat to bypass flow. Auxiliary-exit jet-thrust coefficient, 1.0.

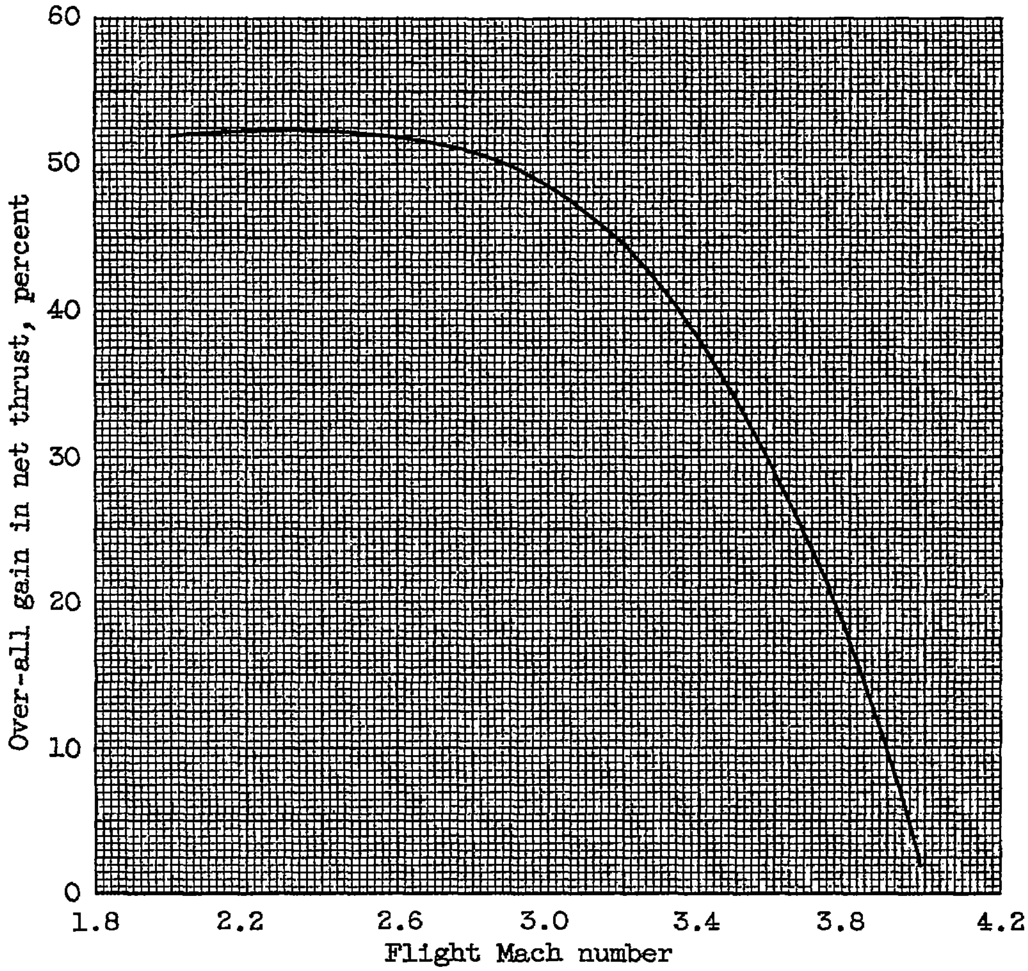

Figure 15. - Over-all gain in thrust by adding heat to bypass flow. Auxiliary-exit jet-thrust coefficient, C_f, 1.0.